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Low-Cost
Solar Array Project

DOE/JPL-1012-38
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LSA Field Test Annual Report August 1978-August 1979

Peter Jaffe

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Prepared for
U.S. Department of Energy
Through an agreement with
National Aeronautics and Space Administration
by
Jet Propulsion Laboratory
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Pasadena, California

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major effort toward the development of low-cost solar arrays.

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ABSTRACT

In the course of three years of testing no evidence has resulted to suggest that the twenty-year-life goal for photovoltaic modules will not be met. Results of studies of more than 600 modules under test show that they are generally enduring well both electrically and physically, particularly those from more recent procurements. Degradation tests performed at JPL indicate that electrical degradation is not a slow monotonically increasing phenomenon as originally thought but occurs abruptly as the result of some traumatic event. This finding has led to a change in the test philosophy. The report includes a discussion of this change, a summary of degradation and failure data from all the sites, results from a variety of special tests, and a description of new instrumentation for in-field measurements. The field testing activity was expanded by the addition of twelve remote sites located as far away as Alaska and the Canal Zone. A description of the new sites is also included.

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SECTION I

INTRODUCTION

This report contains a summary of field testing activities from August 3, 1978 to August 31, 1979. Included is an up-to-date description of all the test sites, including twelve new endurance sites acquired from Lewis Research Center, and a discussion of data acquisition techniques and results. Among the data presented are descriptions of typical evolutions of module degradation, and results from special tests.

Major changes in field testing activities are planned for next year: a large portion of the older modules will be removed, a massive deployment of new modules will occur and a basic change in test philosophy will be implemented. These changes are discussed in Section V of this report.

SECTION II

FIELD SITES

During the past year our network of four test sites was enlarged to include twelve smaller sites originally established by Lewis Research Center in 1977. The sites are located as far north as Alaska and as far south as the Canal Zone and cover virtually all climatic conditions. With the addition of these sites the capability of the field testing network to perform endurance testing has been substantially increased. Using the principal site at JPL to perform in-depth investigations and solve testing problems, the three other Southern California sites to acquire endurance data from the three basic environments (mountain, desert and marine), and the twelve new sites to fill voids in data and complement data from the other sites, the network now offers a complete spectrum of facility capabilities for endurance testing.

A. JPL (PASADENA) SITE

Changes in the JPL facility were minimal last year. Two stands of Block III modules were deployed, the pyranometers were relocated to the south end of the field, and equipment was generally upgraded. Figure 2-1 contains a current layout of the JPL site. The Block III ARCO Solar and Motorola modules were deployed as indicated; the hi-density Solarex modules and the glass Sensor Tech modules were not received and therefore were not deployed. Some difficulties arose with the multiplexers because of moisture in the J-boxes. The problem was solved by installing a system of pressure lines and pumping low pressure dry air into each box.

A number of activities directed toward improving the facility are planned for next year; most of them are already under way.

1. A tape drive unit will be added to the data system. The unit has been ordered and will be delivered in September. With the addition of the unit, all daily I-V data as well as weather, insolation and irradiance characterization data will be archived.
2. A 200-channel DORIC satellite will be added to the data system DORIC data-logger. With this addition, the capability of the data system to acquire and process thermocouple and millivolt data will be increased from 300 to 500 channels. The satellite has been ordered and should be delivered in December.
3. The sun tracker will be brought on-line early in 1980. The current plan calls for utilizing the capability of the data system to drive the tracker. Using the declination angle and equation-of-time tables built into the data system software, and the appropriate algorithms, the tracker will be driven completely by the computer. The strategies for performing this are currently being developed.

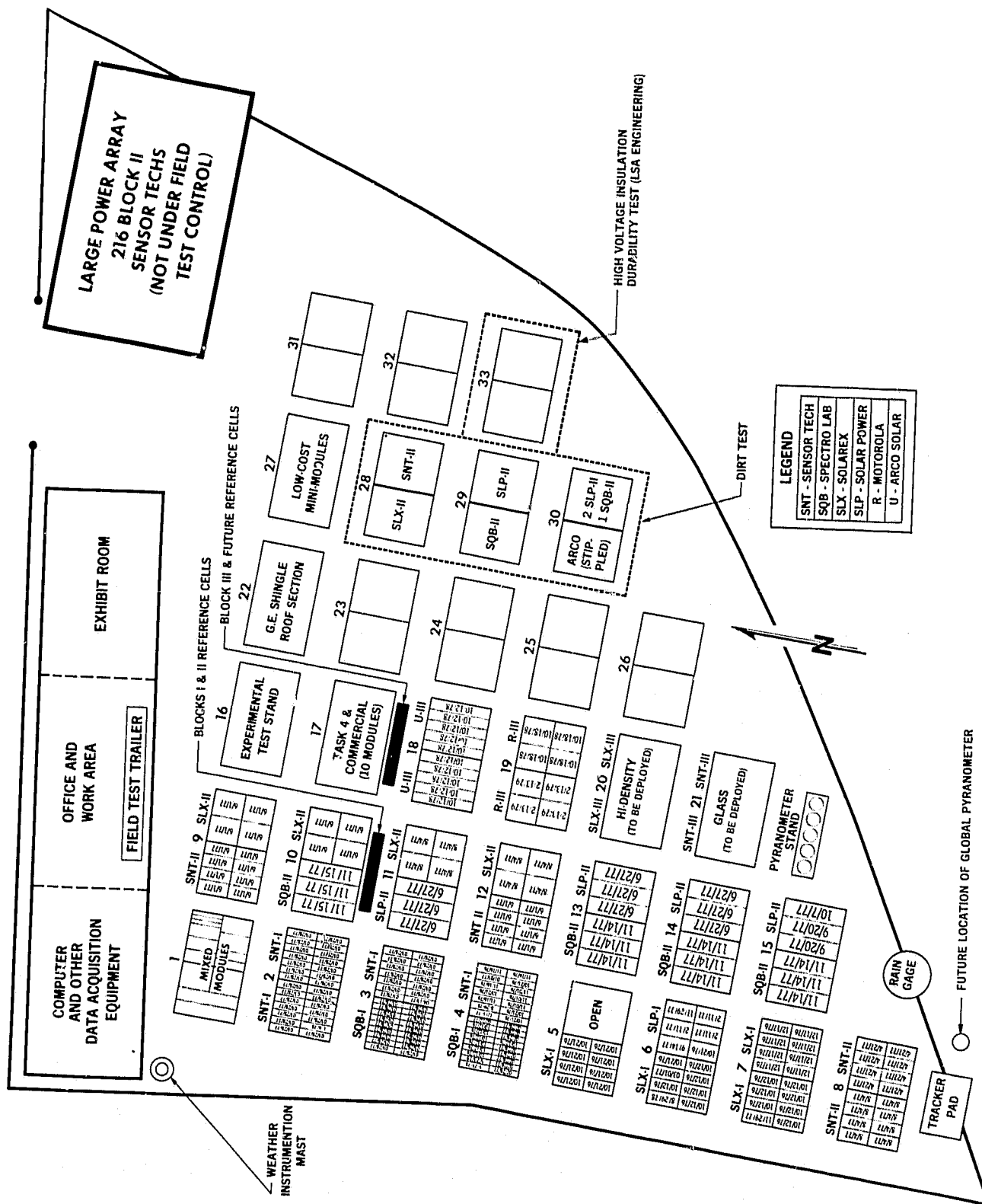


Figure 2-1. Layout of JPL Site

One major problem is how to avoid conflicts between the tracker program, which may have to be active at all times, and other tasks.

4. A pyranometer and pyrliometer pair for measuring the direct, and direct plus diffuse irradiance will be added. Both instruments have been ordered and will be received in the fall. The pyranometer will be mounted on a horizontal platform about five feet east of the tracker. The pyrliometer will be mounted on the tracker.

5. An automatic dew point hydrometer will be purchased and added to the weather gear. Currently, the humidity measurement is the weakest link in the weather gathering instrumentation. With this device the accuracy of the humidity measurement will be substantially increased. The instrument has been ordered and delivery is expected in January.

6. The display room (east end of trailer) will be completely redone. Work has started and completion is expected in December.

B. SOUTHERN CALIFORNIA REMOTE SITES

Figures 2-2, 2-3, and 2-4 contain current layouts of the Table Mountain, Goldstone and Point Vicente sites. With the exception of the Block III modules deployed last year, there have been no changes at these sites. During the coming year a protective fence will be placed around the Point Vicente site. The fence is being installed because of vandalism that occurred at the site last year and the relative openness of the area to the public.

Perhaps the most significant event that occurred at the remote sites last year was the acquisition of high quality data by means of a new portable instrument developed for field testing by the JPL Instrumentation Section. The prospect for the coming year is even better: a new portable instrument capable of taking and recording full I-V curve data with an accuracy level comparable to that of the Field Test Data Acquisition System is being fabricated and should be available early in 1980. A description of both instruments is presented in Section III.

C. CONTINENTAL REMOTE SITES (NEWLY ACQUIRED LEWIS SITES)

Early in 1979 responsibility for the twelve endurance test sites and the deployed modules, which were originally established by Lewis Research Center in 1977, was turned over to LSA. From March through September an inspection and data gathering tour of the sites was undertaken. The purpose was to a) obtain baseline physical and electrical data on all the modules, b) make contact with resident personnel, and c) obtain background information necessary to formulate an overall plan to incorporate these new sites into the



SLIP-11	9/23/77	
	9/23/77	
	9/23/77	
SLIP-1	12/15/76	
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POINT VICENTE COAST GUARD STATION

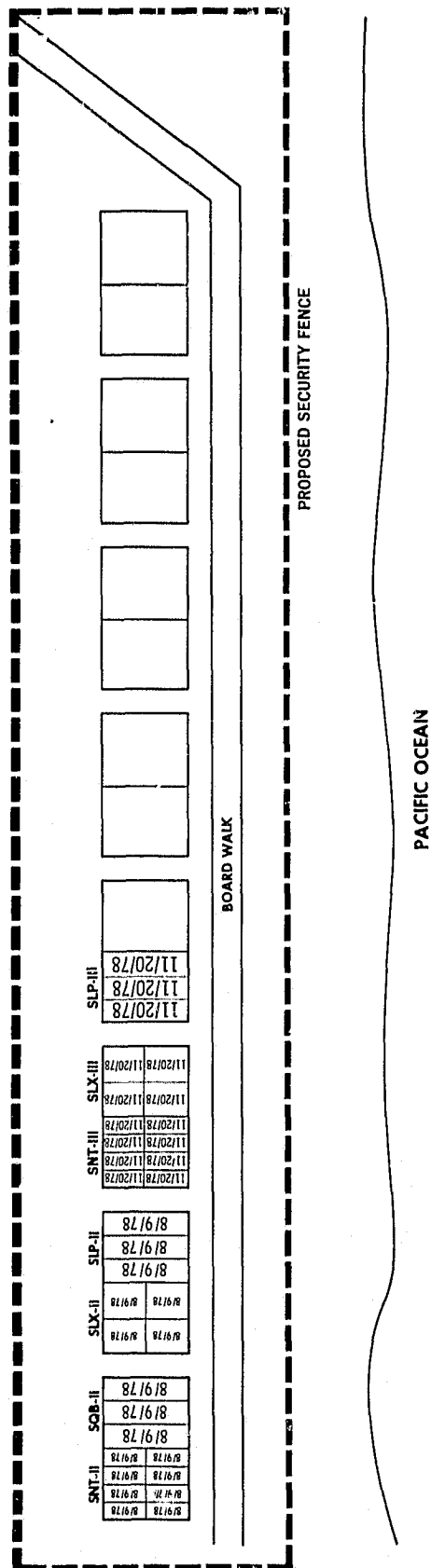


Figure 2-4. Layout of Point Vicente Site

existing network. Figure 2-5 shows the locations of the sites, and Table 2-1 summarizes the key features. Each site has the same inventory of modules: four of each of the Block II modules.* To simulate use in the field each module is loaded with a resistor designed to force the module to operate at conditions close to peak-power. Figures 2-6 through 2-11 contain photographs of the sites by group.

The tour of the sites verified that the network is a valuable asset and should be retained. The broad spectrum of environments represented by the continental remote sites will provide comparative data on the effect of climate which thoroughly complements that obtained at the local sites. The network is already established and stocked with modules, and arrangements for continuing operations are being made with resident personnel. Currently, formal contractual agreements between the site operators and the JPL LSA Project are being developed.

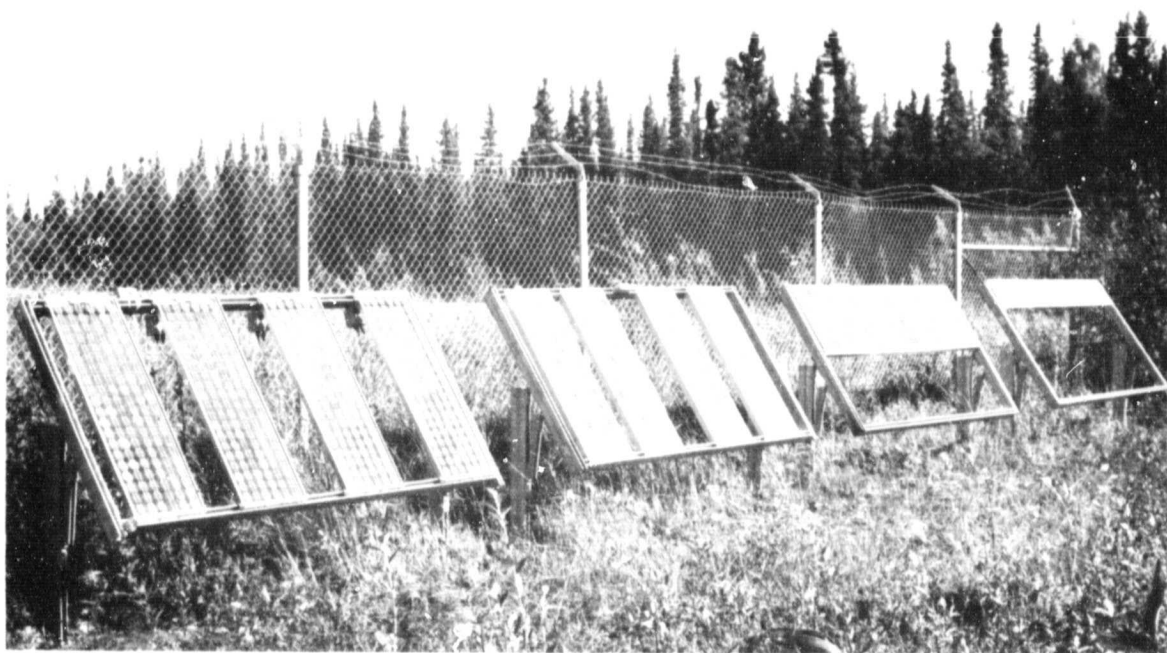
*Block II modules were procured from Sensor Technology, Inc., Spectrolab, Inc., Solarex Corporation, and Solar Power Corporation.

Table 2-1. Summary of Continental Remote Sites

Category	Location	Latitude (degrees)	Altitude (feet)	Key Features
Extreme Weather	Canal Zone (Ft. Clayton)	9	~0	Typical tropic: hot and humid; 100 inch-per-year rainfall
	Alaska (Ft. Greely)	64	1,270	Subarctic environment; ~30°F winters
Marine	Key West, Fla.	25	0	Hot and humid; corrosive salt spray
	San Nicholas Island, Calif.	34	0	Somewhat milder than Key West
Mountain	Mines Peak, Colorado	40	13,000	Clear and cold; high-velocity winds; maximum UV
High Desert	Albuquerque, New Mexico	35	5,200	Dry with clear skies; an abundance of UV
	Dugway, Utah	40	4,300	Cold winters, hot summers; alkaline soil
Midwest	Crane, Indiana	39	~0	Typical midwest: hot humid summers, cold snowy winters
Northwest	Seattle (Ft. Lewis)	47	~0	Typical northwest: mild temperatures and an abundance of rain
Upper Great Lakes	Houghton, Michigan	47	750	Mild summers, severe winters
Urban Coastal	New London, Connecticut	41	0	Typical New England coastal
	New Orleans, Louisiana	30	~0	Hot and very humid; high pollution environment

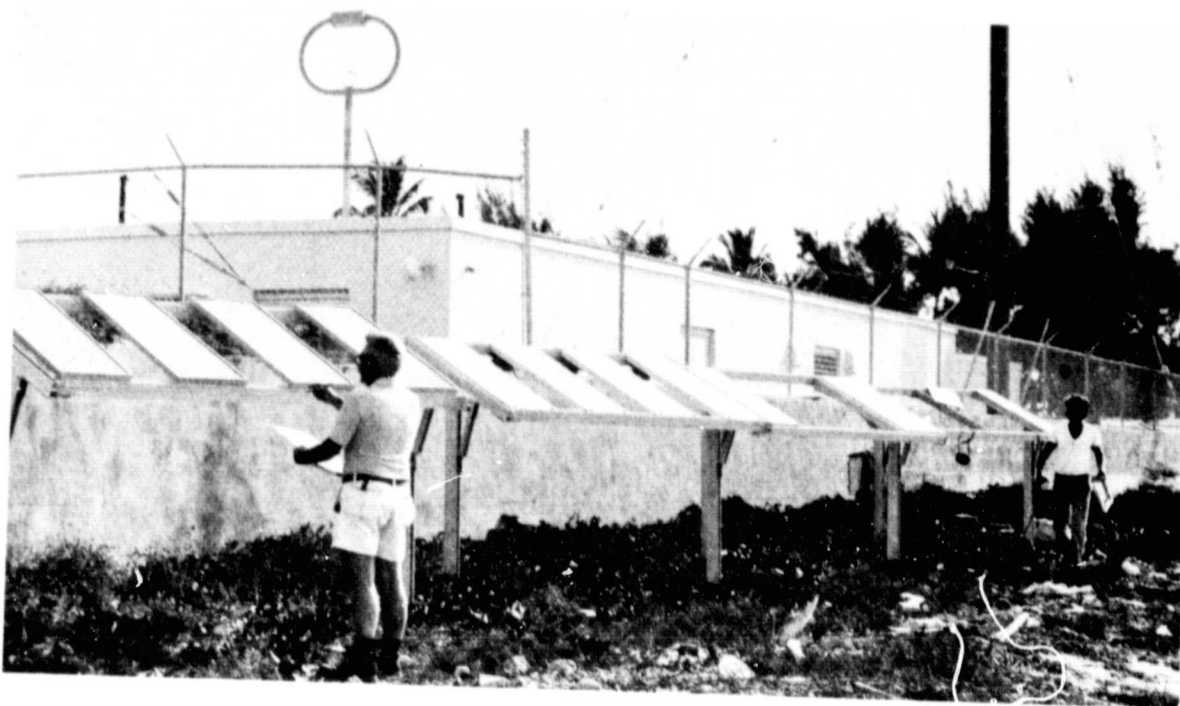


Fort Clayton, Canal Zone

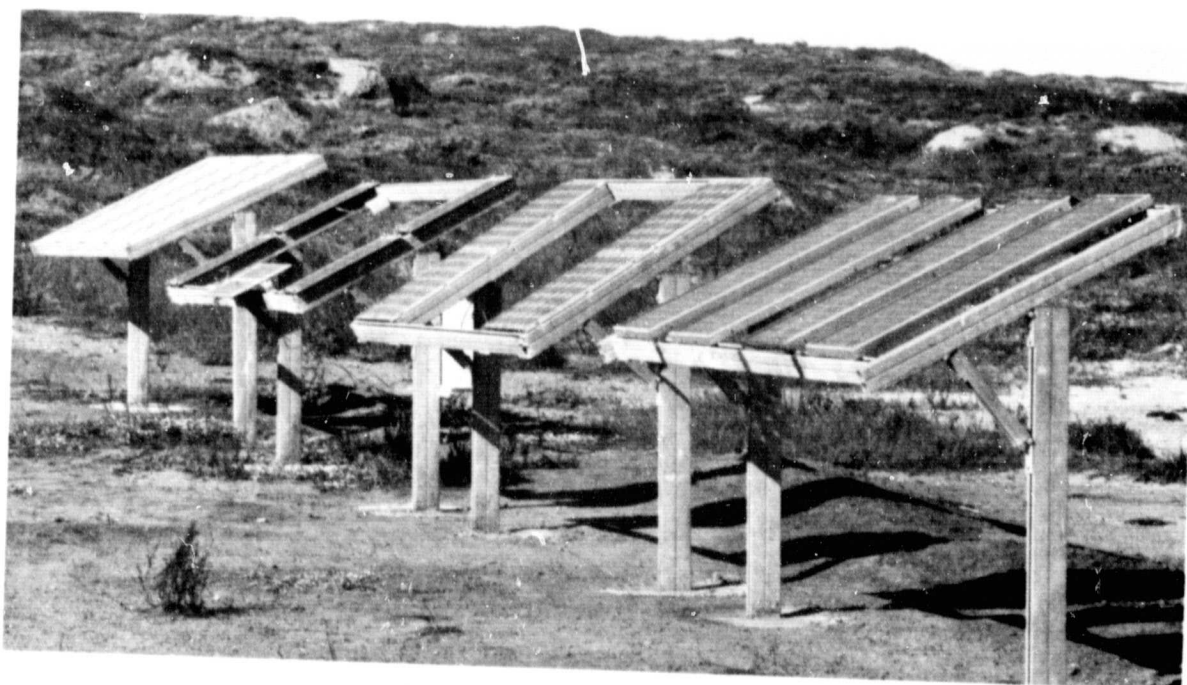


Fort Greely, Alaska

Figure 2-6. Extreme Weather Sites



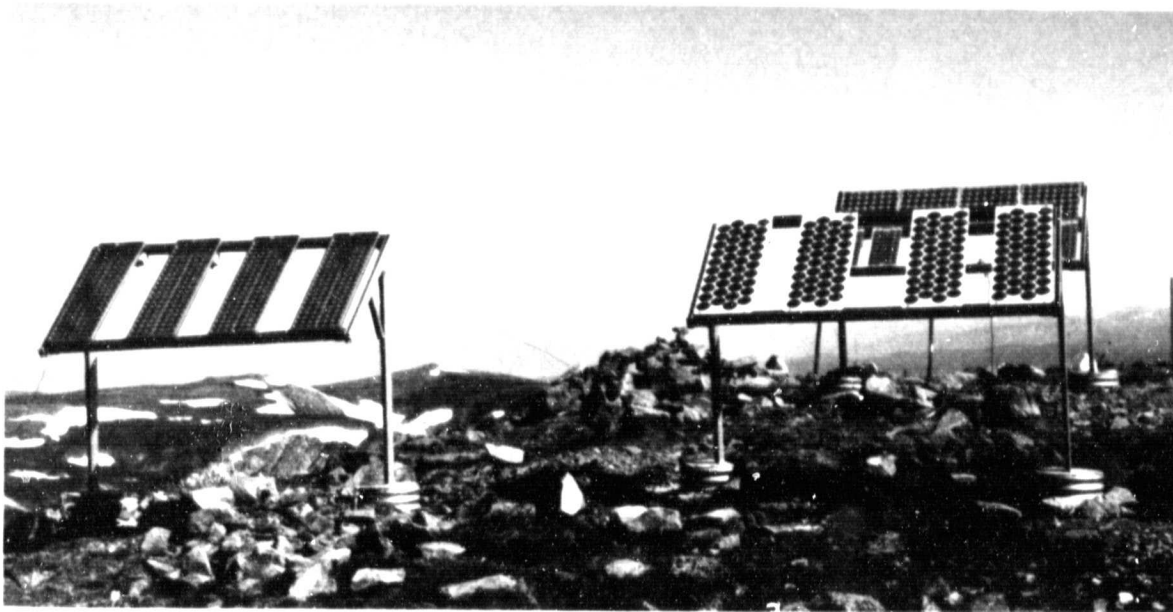
Key West, Florida



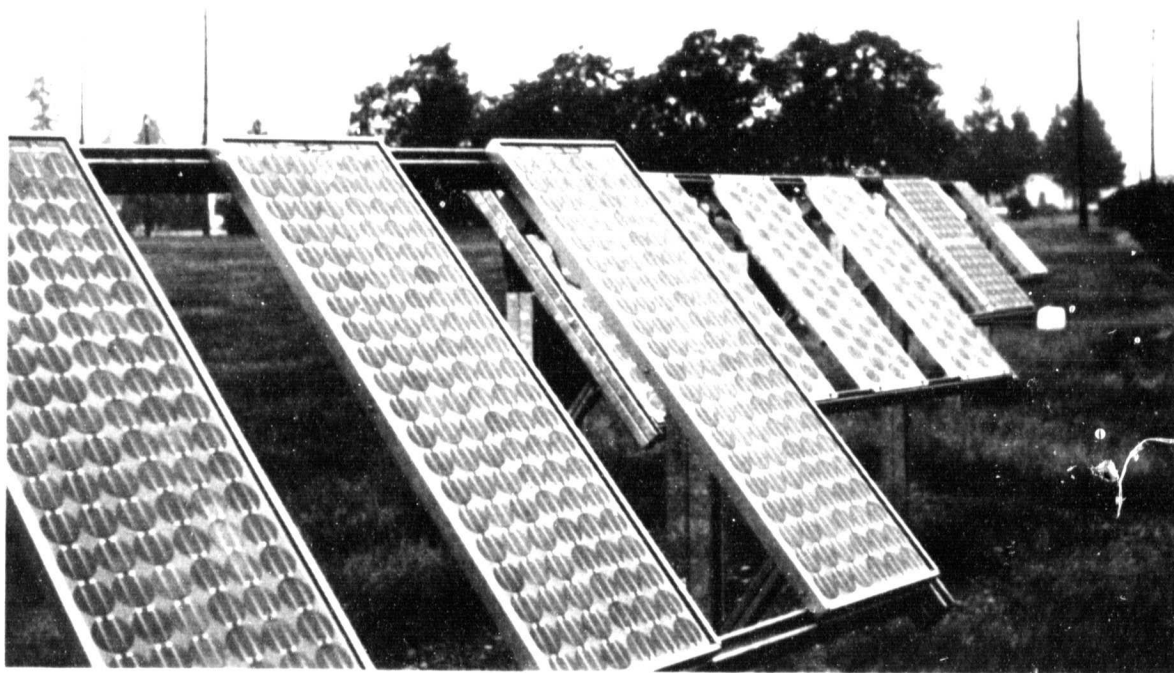
San Nicolas Island, Calif.

Figure 2-7. Marine Sites

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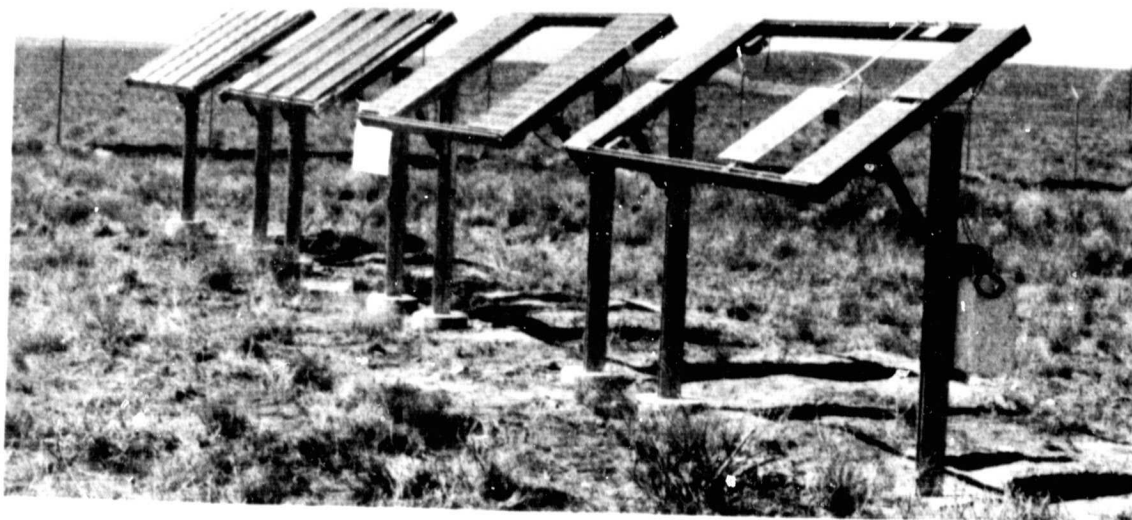


Mines Peak, Colorado

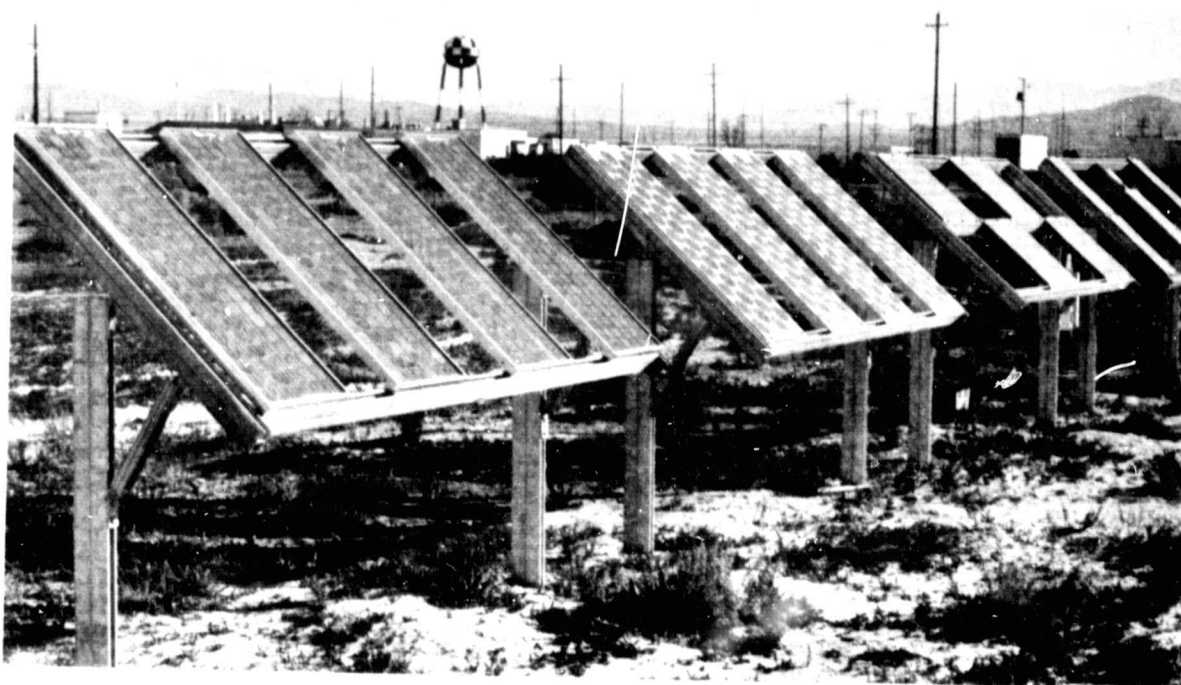


Fort Lewis, Washington (Seattle)

Figure 2-8. Mountain and Northwest Sites

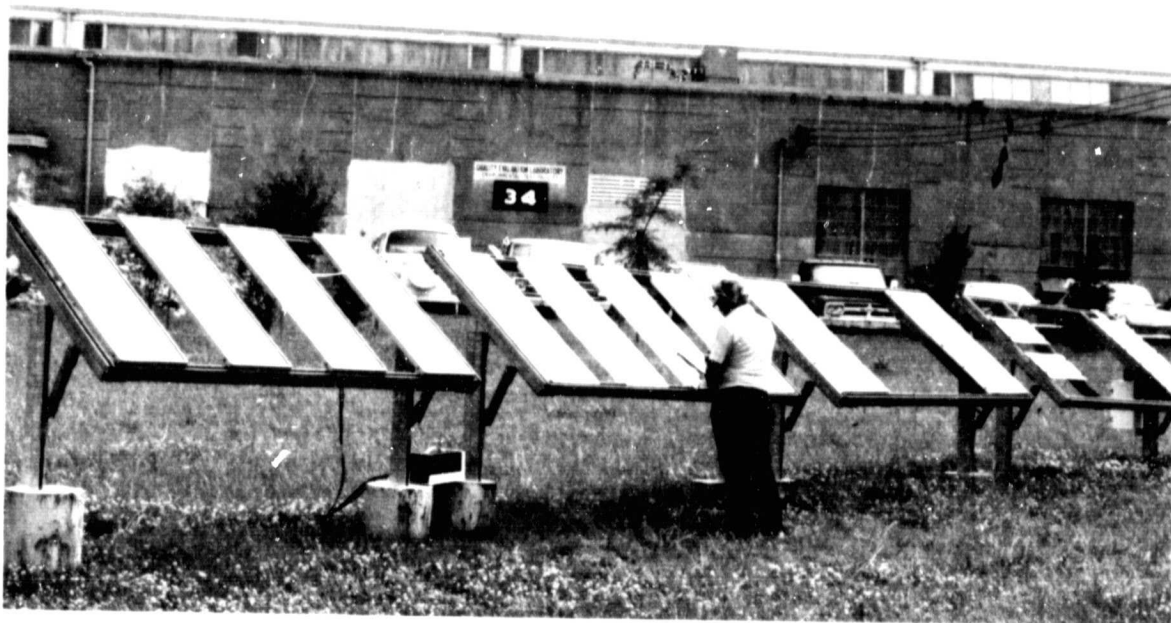


Albuquerque, New Mexico



Dugway, Utah

Figure 2-9. High Desert Sites



Crane, Indiana



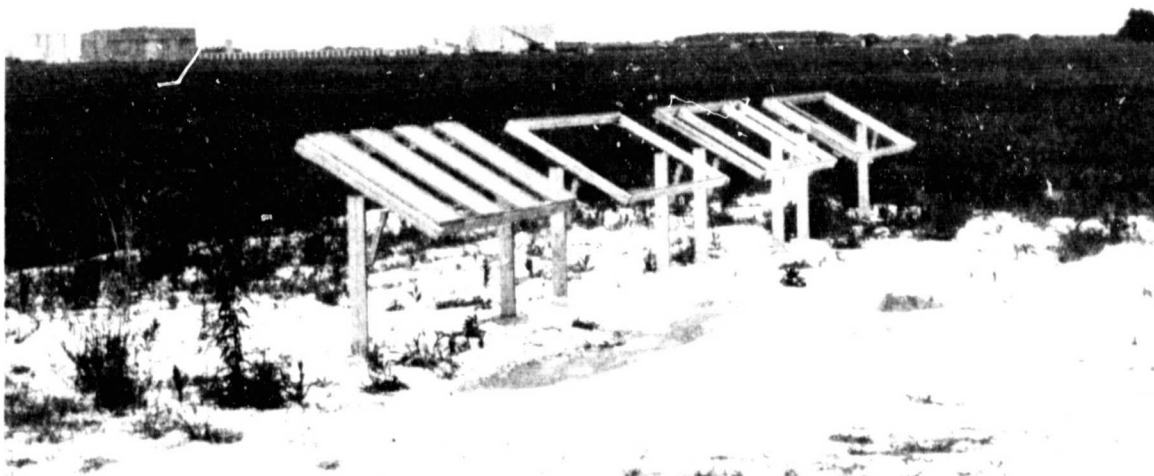
Houghton, Michigan (Winter of 78-79)

Figure 2-10. Midwest and Upper Great Lakes Sites

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New London, Connecticut



New Orleans, Louisiana

(Eleven modules were stolen in early 1979.
All but one were recovered and reinstalled.)

Figure 2-11. Urban Coastal Sites

SECTION III

DATA ACQUISITION

A. JPL SITE

Since the data system was brought on-line in March, 1978, a major goal has been to acquire power output degradation data accurate to 1 to 2 percent. Unfortunately, all efforts to accomplish this have been frustrated because of two problems: traceability and measurement accuracy. Most of the modules were installed in the field long before the data system was brought on-line, in some cases almost two years earlier. Attempts at providing accurate traceability between the pre-installation LAPSS (large area pulsed solar simulator) data and the on-line data-system data have not been successful. The reasons for this are: a) inability to determine the effective field irradiance to an accuracy better than ± 4 percent, b) inability to accurately translate I-V curves because of inadequate temperature correction algorithms and constants, and c) inability to factor out the effects of embedded dirt on transmittance. In many cases, as will be shown later, firmly entrenched dirt decreases transmittance, and consequently short-circuit current, by more than 20 percent. Even when traceability can be established, as in the case of modules newly installed, the accuracy limitations caused by the measurement problems of items a and b above combine to prevent the acquisition of 1 to 2 percent degradation data. A summary of these problems and their effects on the data is tabulated in Table 3-1.

During winter and spring of last year several aspects of these problems were investigated. The details and results are presented below.

1. Angle-of-Incidence

The normal test procedure used in the past to perform the daily acquisition was to initiate acquisition when the insolation level reached 85 mW/cm^2 . Typically this occurred between 10:15 a.m. and 10:45 a.m., Pacific Standard Time. The corresponding incidence angle, i.e., the angle between a normal line to the modules (or reference cells) and the sun line, was between 20 and 30 degrees. The key question is how sensitive to the incidence angle is the ratio of the effective irradiance measured by a reference cell, and the effective irradiance of a module in its family as deduced by its short-circuit current. If this ratio changes, an error in the short-circuit current value of the translated I-V curve will result.

To answer this question a series of tests were performed comparing this ratio for a group of 25 modules and their respective reference cells. In one portion of the test the modules and reference cells were placed at different tilt angles at solar noon thus providing controlled incidence angle data, and in another portion of the test data was taken continuously throughout a three-day period thus providing natural incidence angle data.

Table 3-1. Translated I-V Error Budget

Problem Area and Components	Affected Parameters	Potential Error
Embedded Dirt (silicone rubber only)	I_{sc} , Peak-power	20%
Determination of Effective Irradiance via Reference Cells:	I_{sc} , Peak-power	6%
Spectral mismatch between modules and reference cells		
Variations in field of view between modules and reference cells		
Restricted reference cell field of view		
Optical mismatch between modules and reference cells		
Non-global calibration of reference cells		
Large sun/module angle-of-incidence		
Temperature Correction Translations:	Peak-power, V_{oc}	2%
Inadequate translation algorithms and constants		
Insufficient series resistance information		

From an analysis of the data the following conclusions were reached:

- (a) For all types of modules there does not appear to be a significant angle-of-incidence effect at angles below 10 degrees.
- (b) Results differed from module type to module type at angles above 10 degrees.
- (c) For large angles (around 30 degrees) the effect could be as large as 3 percent.
- (d) There appears to be a time-of-day effect; i.e., the results observed one hour before solar noon were different from those observed one hour after solar noon.

As a result of the above test program four changes to the normal test procedure were initiated:

- (a) The sun/module incidence angle test window was reduced to 10 degrees by using more tilt angles. This was accomplished by adding one additional hole in the stand frame supports at 23 degrees. The revised tilt-angle schedule is as follows:

<u>Date</u>	<u>Tilt Angle (degrees)</u>
February 9	45
March 1	34
March 26	23
April 26	15
August 17	23
September 17	34
October 12	45
November 1	50

- (b) The time of acquisition of daily data was changed to solar noon.
- (c) The reference insolation level was changed from 85 to 90 mW/cm^2 to correspond more closely to the noon acquisition.
- (d) A low insolation threshold of 70 mW/cm^2 was established, i.e., data was taken only if the insolation level was above 70 mW/cm^2 at solar noon.

2. Global Reference Cell Calibration

In March a series of controlled tests was performed to determine if the field short-circuit current of a module as deduced by its reference cell would equal the short-circuit current as determined by the LAPSS. It is essential that this be true if traceability between the field data and the pre-installation data is to exist. The procedure was simple: selected modules were taken out of the field, tested with the LAPSS and put back into the field. The subsequent field data for the modules was then translated to 100 mW/cm^2 (using the reference cell data) and compared with the LAPSS data. Usually the short-circuit current values disagreed, occasionally by as much as 10 percent. The obvious explanations are that the reference cells had changed since originally calibrated or that the original reference cell calibrations were incorrect and/or not compatible with actual use. The true explanation may very well be a combination of the two plus other factors that are difficult to identify. What is known, however, is that the manner in which the reference cells were calibrated does not correspond to the way they are used. Calibrations were performed with essentially the direct component of irradiance by means of collimating tubes. In this way the field of view of the reference cells corresponded to the field of view of the reference

pyrheliometer, which is about 6 degrees. In actual field use their field of view is close to 180 degrees. Considerable controversy exists currently regarding the construction and calibration of reference cells for global use. A discussion of this problem is beyond the scope of this report and will not be presented here. However, because of the need to reconcile the traceability problem, an in-field test program designed to calibrate the reference cells in the manner in which they are used was undertaken. The approach employs the use of transfer modules. These are modules that are removed from the field, tested with the LAPSS and placed back in the field. The LAPSS data from these modules are used to correct the calibration values of the reference cells so that the field short-circuit current values at 100 mW/cm^2 correspond to the LAPSS values.

The in-field calibration took place during a three week period in June. Twenty-nine transfer modules, at least two from each family (module type) were employed. Data was taken in the routine manner near solar noon and corrected to LAPSS conditions (100 mW/cm^2 and 28°C), and reference cell correction factors were determined. In a week during which the sky conditions were steady the correction factors for a module varied typically by less than 0.5 percent. From module to module the variation was generally about 0.3 percent; in one instance it was as large as 6 percent. Earlier tests performed with 10 ARCO Solar modules corroborate those results. After several iterations, a new set of reference cell constants was formulated. In all cases except one, the new calibration constants (the numbers by which the raw millivolt reading are multiplied) were higher. Typically, the increase was 4 percent. One constant was up 10 percent and two were close to zero.

An encouraging note is the result for the Block III modules, ARCO Solar and Motorola. The reference cells for these two modules were placed into the field only a few months before the in-field calibration after being calibrated with the standard procedure using a collimating tube and the most up-to-date technique and equipment. The correction constants for these two module types were 1.4 and 2.6 percent, respectively, differences that could easily be attributed to measurement accuracy. Although not conclusive, these data suggest that calibrations using the direct irradiance component may be satisfactory for global use.

3. Effects of Embedded Dirt

In the process of acquiring transfer module LAPSS data a very important observation was made. The silicon rubber modules had acquired a firmly embedded layer of dirt which substantially decreased their short-circuit current output. Standard practice before acquiring LAPSS data is to wash the modules with a mild detergent in the same manner that the modules in the field are washed weekly. After obtaining the LAPSS data on the transfer modules it was observed that most of the short-circuit current values were down. To investigate further, the modules were subjected to a second washing with a heavy duty commercial detergent and an abundance of "elbow grease". Table 3-2 summarizes the results.

Table 3-2. Embedded Dirt Data

Module Type and Field ID	Installed in Field	Standard Wash % I _{sc} Loss	Second Wash % I _{sc} Recovered
Sensor Tech			
193	6/1/77	15.6	14.1
197	6/1/77	16.0	9.2
198	6/1/77	17.1	12.0
Spectrolab			
189	11/14/77	-1.4	
190	11/14/77	-1.7	
191	11/14/77	-0.9	
Solarex			
212	8/4/77	19.9	14.9
213	8/4/77	21.2	14.1
214	8/4/77	21.5	13.5
215	8/4/77	19.4	15.5
Solar Power			
209	6/27/77	15.6	14.0
210	6/27/77	15.6	12.5
211	6/27/77	19.2	15.6

Typically the modules had been in the field almost two years. As anticipated the glass Spectrolab modules showed no short-circuit current loss; the minus sign means they actually improved. This has been observed before with many Block II Spectrolab modules and came as no surprise. The silicone rubber modules as a group experienced an average loss of 18.1 percent. After the second washing they recovered an average of 13.5 percent of the loss. Subsequent tests with other modules indicated that in many cases apparent short-circuit current losses can be progressively reduced by additional washing, scouring, and rubbing, but they also showed that it is virtually impossible to tell when all the dirt is out.

Even though a specific process for attaining "perfect cleanness" was not achieved it was felt that progress toward traceability would require some heavy duty washing. Therefore, in mid-June all modules interrogated routinely with the data system were scrubbed and scoured. On June 22, after installing new reference cell constants (refer to A2 of this section), a special test was made in which the data were corrected to 100 mW/cm² and 28°C and compared with the pre-installation LAPSS data. The results show that the short-circuit current data fell into the grey area in which it was impossible to tell whether the modules had or had not changed. The short-circuit

current differences for the silicon rubber modules were about the same as those observed after the second washing. The conclusion, unfortunately, is that for silicone rubber modules traceability is virtually impossible because of the inability to quantify the loss of transmittance due to embedded dirt.

B. REMOTE SITE INSTRUMENTATION

One of the recognized deficiencies in the whole testing area has been the lack of instrumentation for acquiring basic electrical performance data from modules at the remote sites. Last year a program to correct this situation was started. The requirements of field testing are such that two specific but very different instruments are needed: a simple, sturdy instrument capable of obtaining basic performance data and a complex instrument capable of acquiring full I-V data. An instrument of the first type was fabricated and placed into service last year, and design and fabrication of the second kind was started. The details are presented below.

1. Photovoltaic Test Meter

The Photovoltaic Test Meter (PTM) is a portable instrument designed to measure in-situ the key module electrical performance characteristics, short-circuit current (I_{sc}), open-circuit-voltage (V_{oc}) and peak power. The instrument is battery-powered and weighs about 7 pounds. V_{oc} is obtained by measuring the voltage directly across the module leads and short-circuit current is obtained by measuring the voltage drop across a 0.2-ohm precision resistor. Peak-power is obtained by means of an electronic variable load. Starting at V_{oc} (zero current) the load continues to draw current through the module through peak-power. Power is determined by multiplying the voltage and current along the way. The sweep time is less than 0.5 second.

Both bench and in-field calibrations of the instrument were performed. The results of those calibrations indicate that the end points, I_{sc} and V_{oc} , are accurate to 0.5 percent and the peak-power is accurate to 3 percent. The 3 percent value was determined by comparing peak-power readings obtained with both the PTM and the Field Test Data Acquisition System on a variety of different modules. Future refinements planned for next year should reduce the error to about 1 percent.

The instrument has two operating ranges: 40 volts at 2 amperes and 10 volts at 10 amperes. In addition it has an input option to accommodate a reference cell. The outputs are presented in digital form on a liquid crystal display. The different output options are obtained by means of a rotary switch. The procedure in the field is to switch to the reference cell position and wait until the insolation is steady. The insolation value is then hand-recorded and the operator cycles through the switch positions: I_{sc} , V_{oc} and peak-power.

With two people, one calling out the values and the other recording them, it takes about 15 seconds.

2. Portable I-V Data Logging Instrument

As conceived, the portable I-V data-logger will be an instrument capable of obtaining full I-V data from a module in the field, simultaneously acquiring the necessary peripheral information such as module temperature and reference cell data, and storing this data in a medium which can be off-loaded into the Field Test Data Acquisition System at a later time. Its accuracy would be almost on a par with the Field Test Data Acquisition System and the sweep time would be under a second. Conceptually, in order to accommodate these requirements a microprocessor would be employed. The design of this instrument was completed last year and the first phase of the fabrication started. Further details are given below.

- a. The data acquisition system will consist of two major components: A portable battery powered microprocessor-based instrument for the acquisition and storage of data, and a second instrument for transmitting the stored data to the Field Test PDP 11/34. The acquired data will be stored on removable reusable media.
- b. The storage media will consist of removable EPROM units which are small and durable, are relatively insensitive to their environment and have no moving parts.
- c. Maximum input voltage and current will be 30 volts and 10 amperes. There will be two voltage ranges, 15 and 30 volts and two current ranges, 2 and 10 amperes. Voltage and current readings will be accurate to $\pm 0.5\%$ of the range value. The instrument will be able to tolerate voltage inputs as high as 60 volts without causing damage to internal electronics and will also be protected against reverse voltage module inputs.
- d. The acquisition of I-V data will be controlled by the microprocessor's software. This permits the acquisition algorithms to be modified on the bench with no hardware changes, thus greatly increasing system flexibility. The current acquisition strategy is to start at zero current (V_{OC}) and increase the current according to the change of slope of the I-V curve. Beyond peak-power, where the curve is more sensitive to voltage, the increment variable will be changed to voltage. Breaking the curve into two sections provides a neat method of optimizing the acquisition process. At least 30 I-V points will be obtained on a curve.
- e. Provisions for six channels of peripheral information will be provided. These will include two channels for thermocouples, and two channels each in the 10-millivolt range and 100-millivolt range for reference cells, pyranometers and

other inputs. The accuracy will be $\pm 0.5\%$ of the specified range for the millivolt channels and $\pm 5^{\circ}\text{C}$ for the thermocouple channels.

- f. A keyboard coupled with a liquid crystal display will be provided for initiating data retrieval and entering identification log numbers and module ID. Using the keyboard, the operator will be able to recall and display V_{oc} , I_{sc} , peak-power, fill-factor, module temperature, pyranometer reading and reference cell reading from the last acquisition.
- g. The instrument will contain an internal reference. A calibration check will be performed by the microprocessor prior to taking any measurements. Abnormal readings will be indicated to the operator but will not inhibit data collection.
- h. The acquisition instrument will use rechargeable batteries capable of providing at least two hours of continuous operation. Its weight will be about 45 pounds.

Completion and checkout of the data logging instrument is expected in January. The interface instrument is expected to be completed in February. If all goes according to plan the portable I-V data logger will be in operation by March 1980.

SECTION IV

TEST RESULTS

A. JPL SITE DEGRADATION DATA

1. General

Electrical degradation falls into two categories: the slow monotonically increasing type resulting from material deterioration, and the spontaneously developing type resulting from some traumatic event such as a cracked cell or interconnect separation. To date none of the first type has been observed; all of the electrical degradations appear to fall into the second category. A module may go from the original stable condition to a second stable but degraded condition, or the degraded condition may become progressively worse. Occasionally, the degraded condition is unstable, appearing when the module is warm and disappearing when it is cool. To illustrate the extent of the problem of identifying and categorizing a degraded module, the following example is presented.

Module 211 was recently taken out of the field and interrogated with the LAPSS in connection with the reference cell investigation. The LAPSS data, taken at room temperature, showed the module to be in excellent condition, with no change from previous LAPSS interrogations. Visually the module looked fine also. A review of past field data revealed that the power output of the module had been down intermittently for some time. To trace the problem, data was taken in the field several times during the same day and over a period of several days. Figure 4-1 shows a sequence of I-V curves produced by the Field Test Data System on the same day. (The I-V curves are rotated 90 degrees from their normal orientation. The numbers 21 and 1.8 refer to the maximum voltage and current plot scales, respectively. The voltage (ordinate) axis of the lower curves was suppressed to condense the graph. Tick marks on the right side of the figure indicate the origin for each of the ordinate axes.) The data was taken at 10:09, 10:44 and 11:22 a.m.; the corresponding module temperatures were 45.4°C, 46.3°C and 49.2°C. As shown in the figure, at 45°C the module was functioning fine, but a degree or so later it appears badly degraded. To add to the confusion, data obtained on other days indicated that the degraded curves did not always look the same and that the onset of degradation did not always occur at the same temperature. Ambiguous data of this type is symptomatic of unstable degraded modules. It is obvious from this example that caution must be exercised when concluding that a module is either good or bad.

2. Degradation Data Survey

In preparation of this report, an extensive review of the I-V histories of all the routinely interrogated modules was performed. Following are some overall conclusions about module degradation and

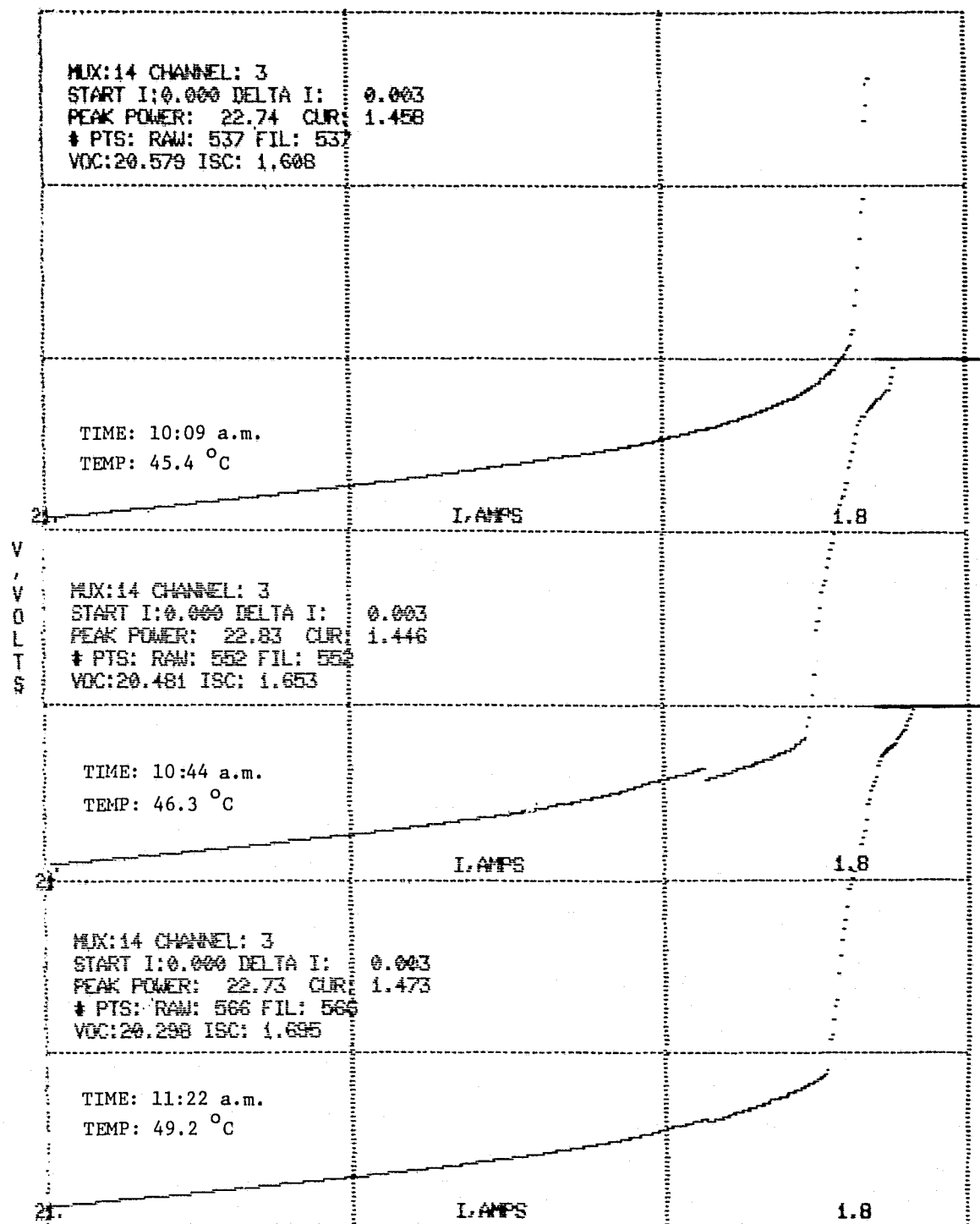


Figure 4-1. Effects of Temperature on Module 211

the methods which must be used to detect them. (Degradation statistics from the survey are presented in paragraph B of this section.)

- (a) When a module changes, it is generally not a subtle change but a dramatic one.
- (b) The principal cause of degradation is the cracked cell. However, the nature of the resultant I-V abnormalities varies considerably with the type of module, and the type and location of the crack.
- (c) Abnormal behavior of a module's I-V curve is generally related to physical problems within the module. As a consequence the degraded module often responds to physical changes such as temperature or pressure.
- (d) To characterize an I-V curve as abnormal, it is necessary to refer to a reference curve of the module before degradation occurred. Merely looking at an I-V curve to determine if a module is degraded can be misleading.

To provide an overview of the findings four representative case studies are presented.

Case Study 1. Module 101 is a degraded module that has been under observation for a long time. A sequence depicting the evolution of its change is seen in Figure 4-2. (Tick marks on the right side of the figure indicate the origin for each of the ordinate axes.) Prior to March 2, 1979, module 101 showed no abnormalities. Within a few days after March 2 this module's normal looking I-V curve (Figure 4-2(a)) exhibited a sudden discontinuity (Figure 4-2(b)). The I-V curve continued to vary and one month later a normal I-V curve was again seen. Subsequently, other strange shapes in the curves appeared (Figure 4-2(c)) and eventually a stable but degraded condition developed (Figure 4-2(d)). Module 101 has a cracked cell which undoubtedly accounts for its degradation. Unfortunately neither the date nor the origin of the crack is known.

Case Study 2. The cause of the erratic behavior of I-V curves is not always obvious nor can it be attributed to one particular mechanism. Figure 4-3 shows the I-V curves of two different degraded modules which have exhibited erratic behavior of a similar nature. Module 113 (Figure 4-3(a)) was tested at several temperatures and found to be sensitive to temperature. Since the I-V curve of module 156 (Figure 4-3(b)) resembles the curve of module 113, it is natural to assume that this module is also sensitive to temperature; however, it is not. It was discovered that when pressure was applied to the module near one of the interconnects, the voltage reading went up to the normal value. When the pressure was released the voltage dropped and fluctuated. Undoubtedly this module has a bad interconnect junction.

Case Study 3. Although detailed correlations are difficult to make, some overall trends in the shape of I-V curves of the degraded modules

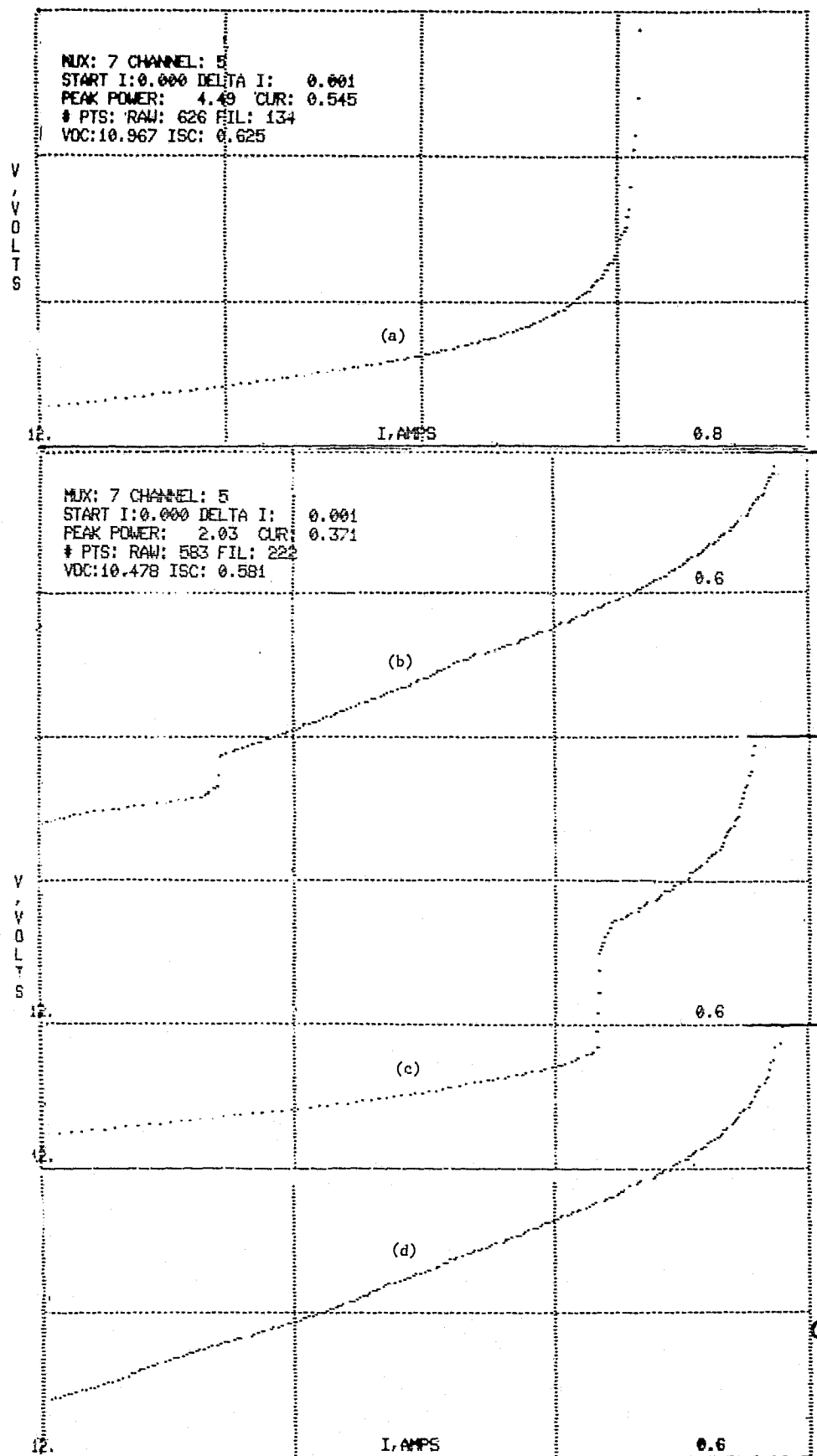
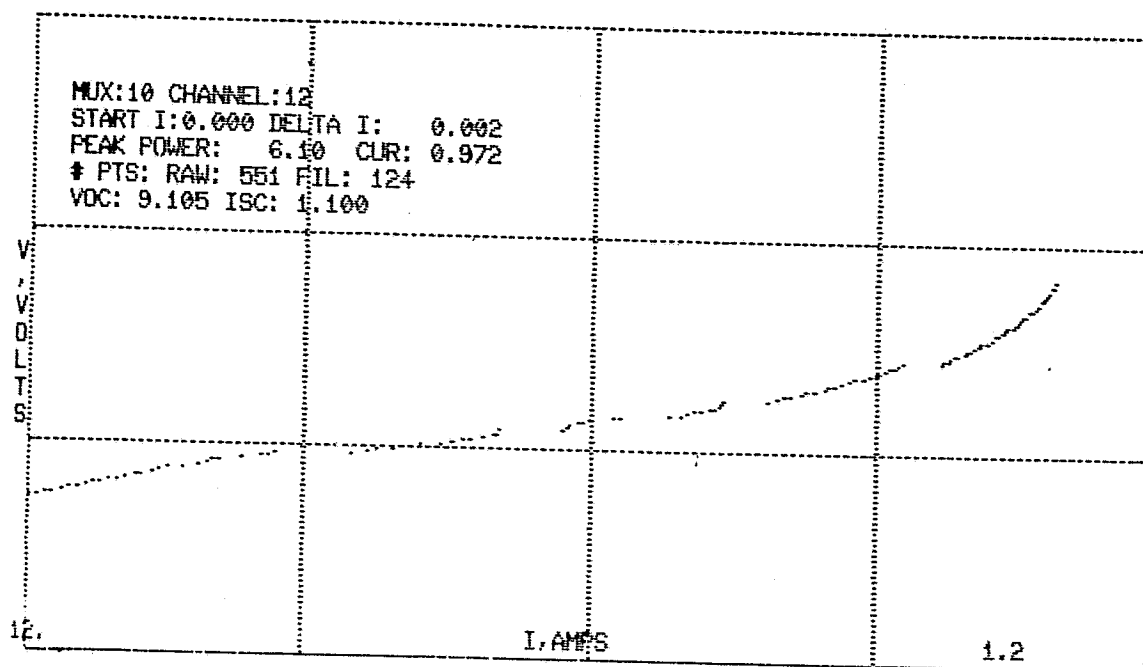
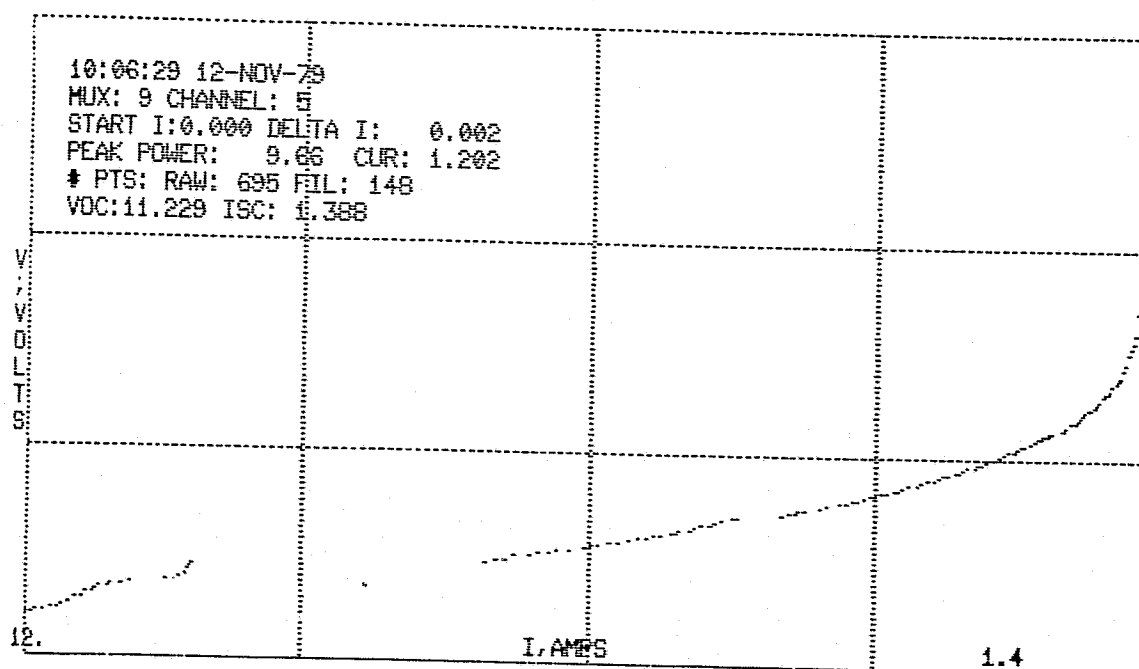


Figure 4-2. I-V History of Module 101

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(a) Module 113 - Temperature Sensitive



(b) Module 156 - Pressure Sensitive

Figure 4-3. I-V Curves of Two Erratically Behaving Modules

have been observed. In March of last year there was a hail storm which cracked cells in many of the modules. One particular type of module, Sensor Tech Block II, was particularly vulnerable to the hail and experienced many cracks. An inspection performed by Quality Assurance indicated that each of 17 of these modules developed between one and five "impact" cracks, and 12 of the 17 modules later showed degraded I-V curves. The Solarex modules also experienced some hail damage but to a lesser extent. Figure 4-8 contains a photo of one of the impact cracks.

About a month after the hail storm, the I-V curves of the affected modules showed small fluctuations around the knee. The curves continued to change and the knees flattened out. Eventually the I-V curves assumed a stable degraded mode. The curves for module 165 are representative of those observed for the modules in this group. Figure 4-4 illustrates a progression of these curves over a few months. Twelve of the 24 degraded modules are of this family and all of these had I-V curves which resembled those shown in the figure.

Case Study 4. The final case, that of module 160, is an interesting one in which there is a direct observable connection between the degraded I-V history and the appearance of a physical defect. One of the cells in this module developed so much heat as a consequence of operating in reverse bias that a portion of the cell was charred and a hole was burned through the encapsulant. A photograph of this area is shown in Figure 4-9. Several I-V curves at different times in this module's history are shown in Figure 4-5. The upper curve of April 10 shows the module to be operating normally. Two weeks later the first signs of degradation appeared, and by July 31 the module had degraded substantially. It appears to be getting worse and will probably fail completely.

B. DEGRADATION AND FAILURE STATISTICS

A degraded module is essentially defined as a module whose I-V curve has degenerated from its initial shape. This condition is almost always accompanied by a drop in peak-power. At the JPL Site where I-V histories are readily available it is a relatively straightforward matter to determine if a module has become degraded. But, at the remote sites where full I-V curve data are not available another method had to be employed. Since degradation is almost always associated with a drop in peak-power, and a peak-power change results in a fill-factor change, a reasonable solution is to use a drop in fill-factor to deduce degradation. A complete discussion of the rationale behind this was presented in last years Annual Report. Experience at the JPL site has shown that 3 percent is the nominal fill-factor drop level marking the onset of degradation. At the remote sites, using the PTM, 7 percent is used as the criterion. This is based on the accuracy of the instrument, possible variations in the sky when data is taken, temperature differences between the initial test data (often obtained indoors) and the current test data, and uncertainty about the accuracy of the initial data. In actual practice, if the insolation level was low or the sky particularly unsteady at the time data was taken, a greater allowance was made.

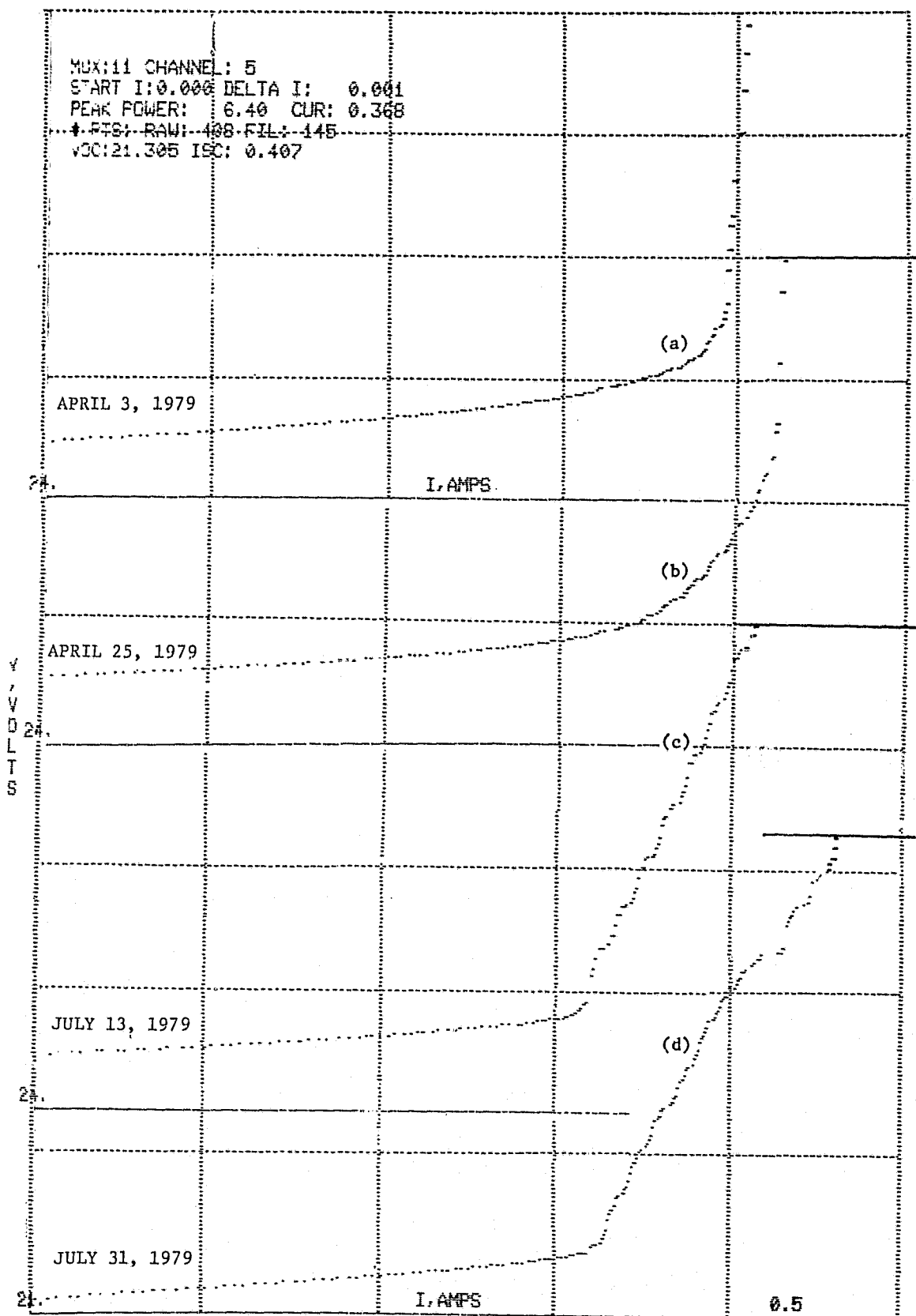


Figure 4-4. Evolution of I-V Degradation for a Module with an Impact Crack

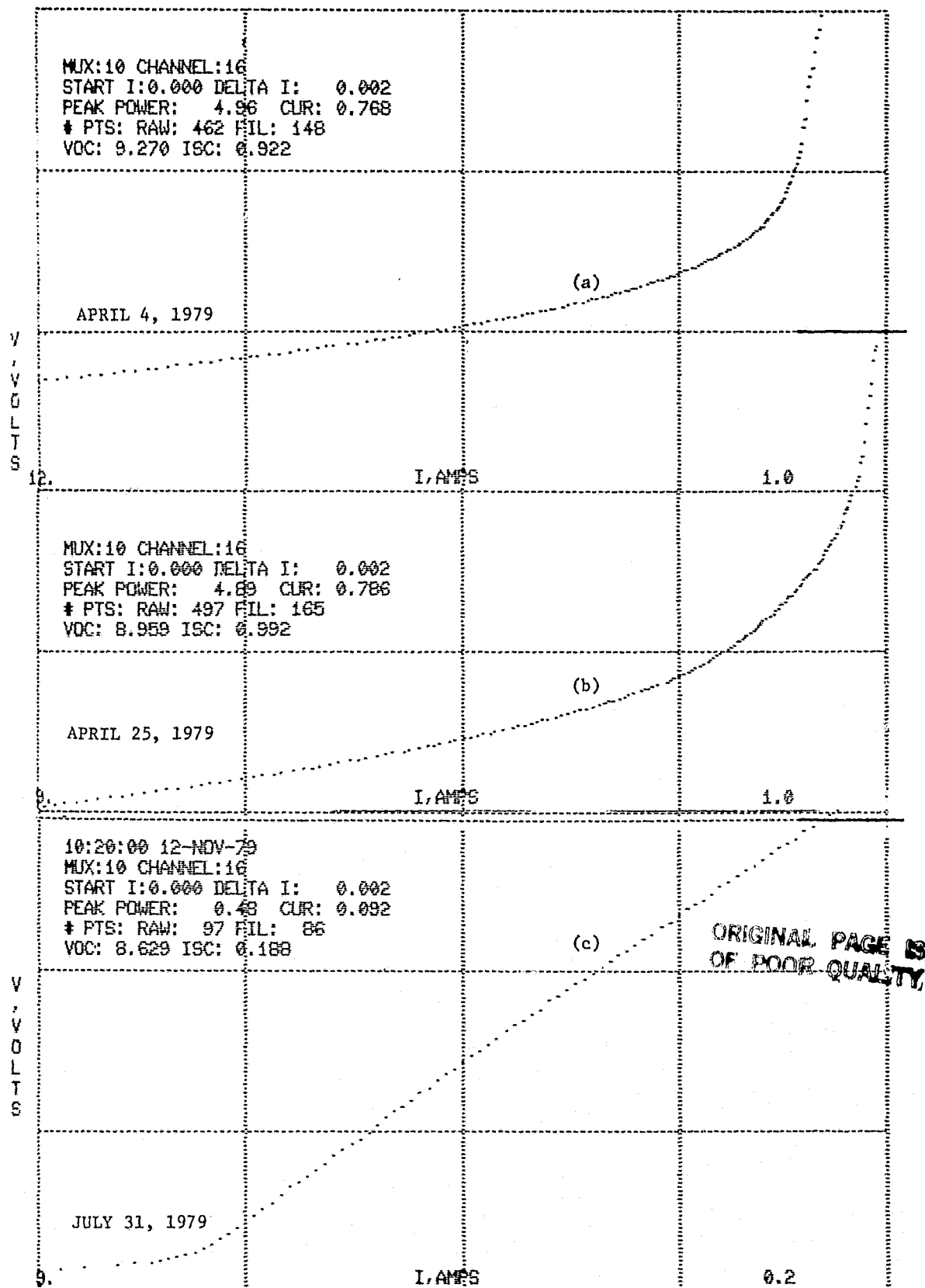


Figure 4-5. I-V History of Module with Cell in Reverse Bias

During last year individual module data was obtained on each of more than 600 modules at the 16 sites. Table 4-1 summarizes the results. The table is organized by site location and module types. "Test Quantity" refers to the sum of modules currently in the field and those that have failed and been removed. A module is considered to have failed when it no longer produces any power. Occasionally a module was removed from the field when it was badly degraded but still producing some power.

As is evident from the table, the percent of modules degraded at the JPL Site is considerably greater than it is at the remote sites. Half of the degraded modules at JPL are Sensor Tech Block II modules, and degradation of all of those is due to impact cracks. If the group is eliminated from the statistics, the JPL numbers look more in line with the others. It is also quite possible that because of the intermittent nature of degradation, the infrequent acquisition of data from the remote sites, and the inability to obtain full I-V curves at those sites, some degraded modules may have gone unnoticed. This situation will be partly rectified when the Portable I-V Data-Logger becomes operational.

A breakdown of the data by site from the Continental Sites is presented in Table 4-2. The numbers in the squares refer to quantity of modules. Included on the table is an overview of the physical status of the modules and stands at each site. A blank space in a "Physical Degradation" category means that signs of physical deterioration observed were "normal" or below in quantity. For example, a blank space for "cracked cells" does not indicate that no cracked cells were observed but rather that a normal or average number was observed. In general both the electrical and physical condition of the modules was good at all sites. A positive exception to this statement were the modules at Mines Peak which looked brand new. There were absolutely no visible signs of deterioration on any of the modules and electrically they were all functioning perfectly. Probably the most harsh environment was Key West with its heat, humidity, and salt-spray air. The salt spray in particular took its toll on all metal parts.

A plot showing the failure rates for the Block I and Block II modules from all the sites is contained in Figure 4-6. The plot speaks for itself. After almost 2-1/2 years the failure rate of the Block II modules is only one-fifth that of the Block I modules. As can be seen in Table 4-1, no Block III modules have failed.

C. DIRT TESTS

Controlled dirt tests started two years ago and were continued last year with one exception: emphasis was changed from washing the majority of the modules routinely to retaining the dirt on the larger quantity of modules. The "dirt retained" group consisted of 14 silicone rubber and four glass modules, and the "wash" group (dirt removed) consisted of three of each. On May 5, after the modules were thoroughly cleaned and I-V data obtained with the LAPSS, they were

Table 4-1. Summary of Electrical Degradation and Failure Data

	Sensor Tech I	Spectrolab I	Solarrex I	Solar Power I	Sensor Tech II	Spectrolab II	Solarrex II	Solar Power II	Sensor Tech III	Solarrex III	Solar Power III	ARGO Solar III	Motrola III	TOTALS
JPL														
Test Quantity	40	37	16	40	16	21	18					10	8	269
Months in Field	28	33	29	25	21	24	22					13	13	
Failed Modules	2	4	12	12		2	3							29
Degraded Modules	2	2	3				4					1		24
TABLE MOUNTAIN														
Test Quantity	14	8	8	8	3	4	3		8	4	3			81
Months in Field	33	34	34	32	31	26	26		10	10	10			
Failed Modules	1		9											10
Degraded Modules	1	1					1							3
GOLDSTONE														
Test Quantity	14	8	6	8	3	4	3		8	4	3			79
Months in Field	34	28	32	27	32	27	27		9	9	9			
Failed Modules			2											3
Degraded Modules			2		1					1				5
PT. VICENTE														
Test Quantity				8	3	4	3		8	4	3			33
Months in Field				14	14	14	14		11	11	11			
Failed Modules														0
Degraded Modules				1					2					3
CONTINENTAL														
Test Quantity				44	48	44	44							180
Months in Field				20	20	20	20							
Failed Modules														2
Degraded Modules				2		1	4							7

Table 4-2. Breakdown of Data from the Continental Sites

MODULES INSPECTED 180												
	Canal Zone	Key West	New Orleans	Crane	Houghton	New London	Mines Peak	Albuquerque	Dugway	Washington	Alaska	San Nicolas Isl.
<u>ELECTRICAL DEGRADATION</u>												
Failed Modules	①*						①					
Degraded Modules	②	①	①		①		②					
<u>PHYSICAL DEGRADATION</u>												
Cracked Cells												
Metallization Discolored/Corroded		•			•		•		•			
Delamination				•								
Frame/Hardware Corrosion		•	•	•	•			•			•	
Connector Deterioration		•			•		•	•	•	•		
Wiring Deterioration												
Embedded Dirt		•	•	•	•		•	•	•	•	•	
Stand Corrosion	•	•	•	•	•			•	•	•	•	

• Moderate Amount before installation

• Substantial Amount

*Encapsulant damaged before installation

placed in the field. On June 20 and October 8, both groups were removed and I-V data obtained. The "dirt retained" group was then replaced in the field while the "dirt removed" group went through an additional cycle of cleaning and LAPSS testing before going back into the field. Figure 4-7 contains the results*.

The silicone rubber "dirt retained" data on the upper graph shows a linear five percent per month decrease in transmittance due to dirt. A comparison of the silicone rubber data on the lower and upper curves also indicates that virtually all the dirt that fell on these modules was retained. In contrast, the glass module data exhibits

*Although the reporting period ends on August 31, this material is presented here because the dirt test program is being suspended and this report provides the most timely opportunity for presenting the results.

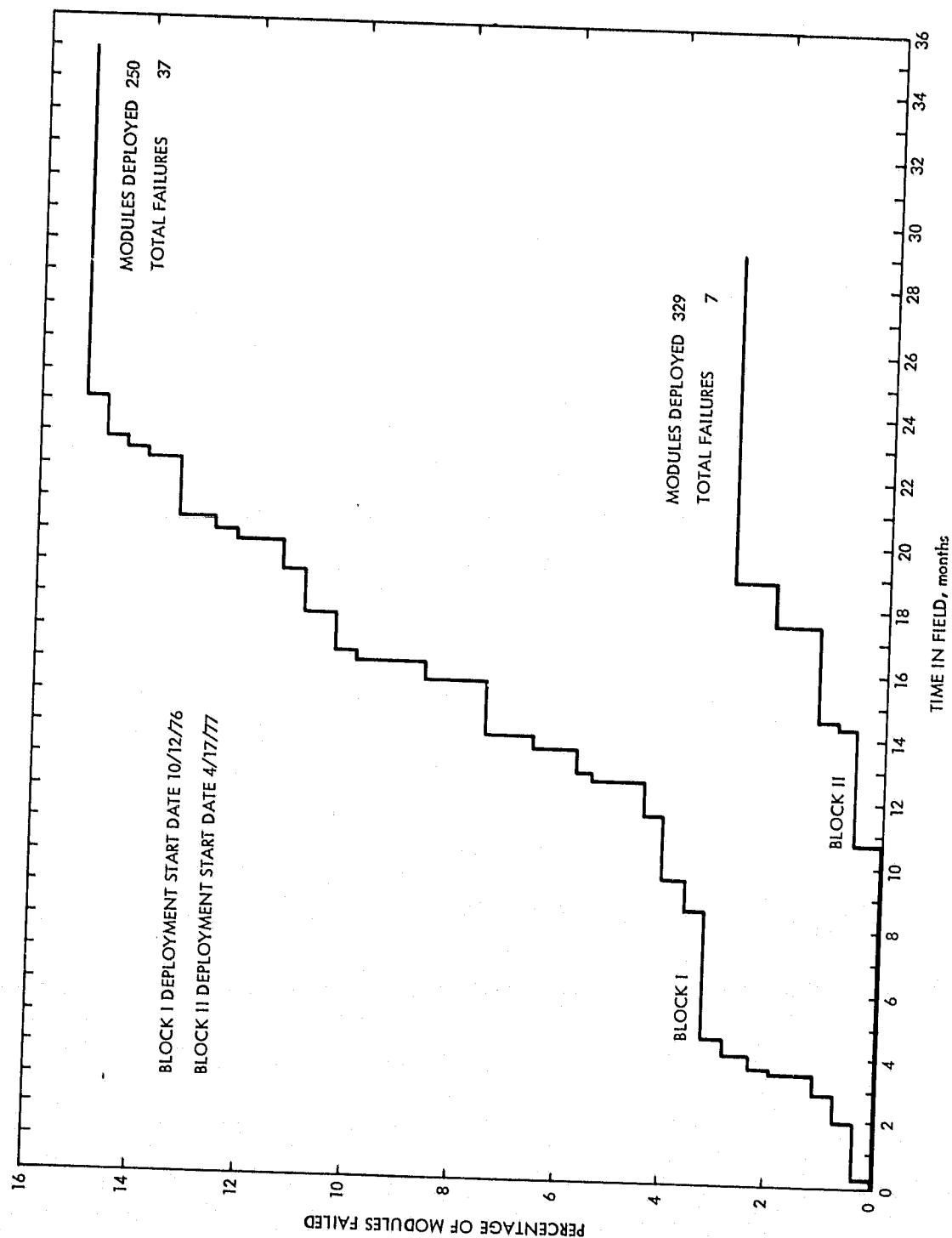


Figure 4-6. Failure Rates for Block I and Block II Modules from all Sites

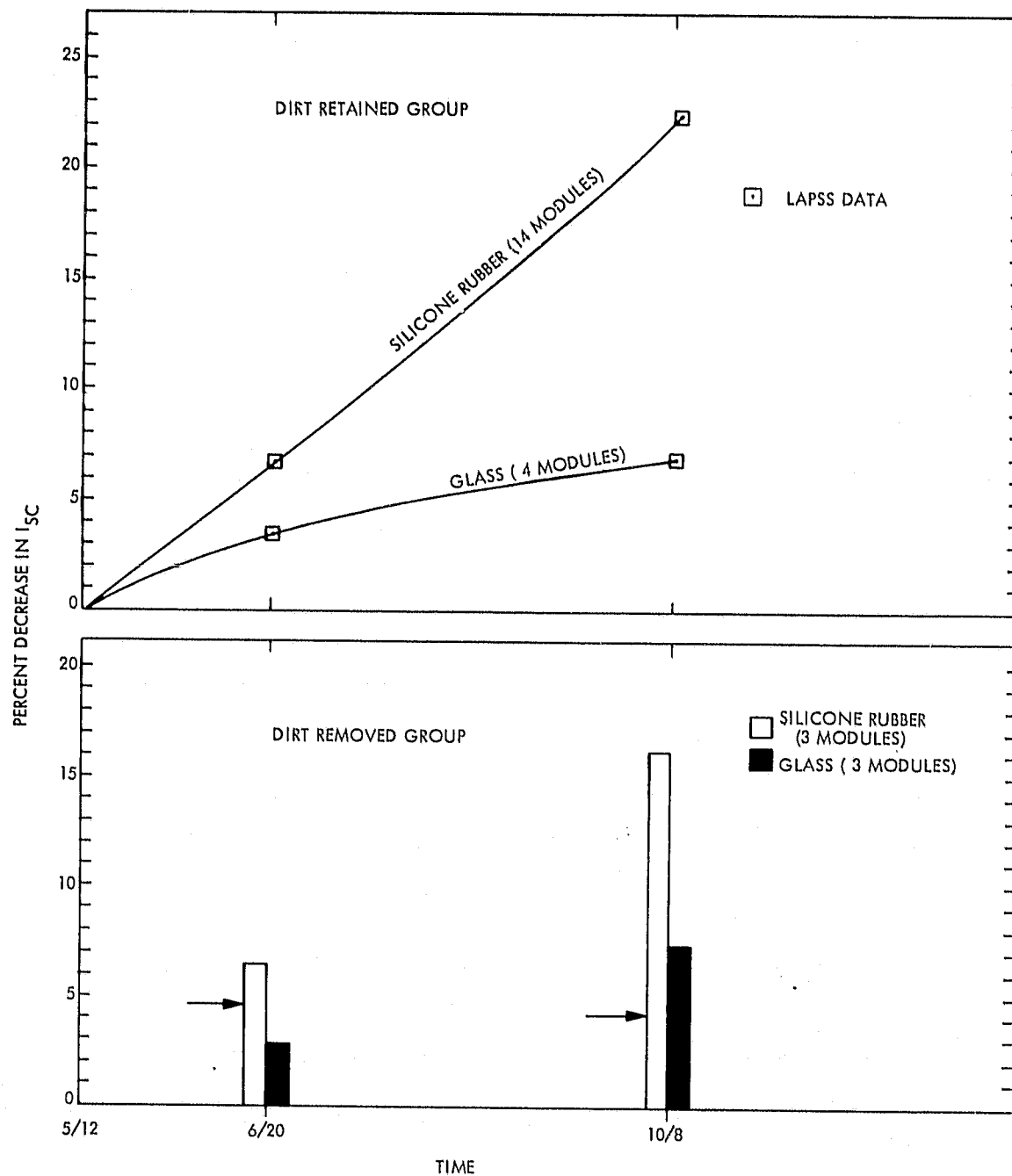


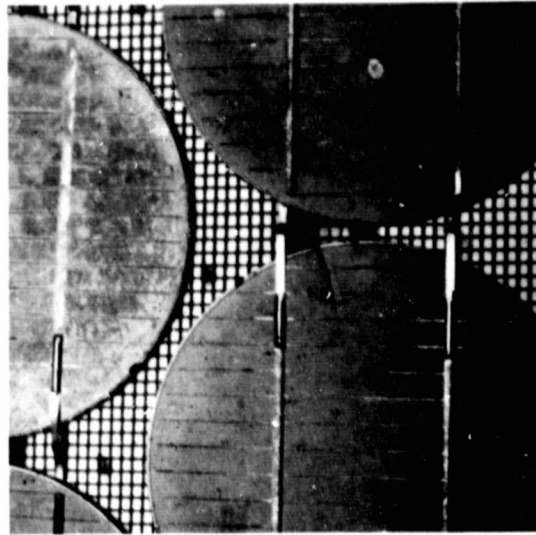
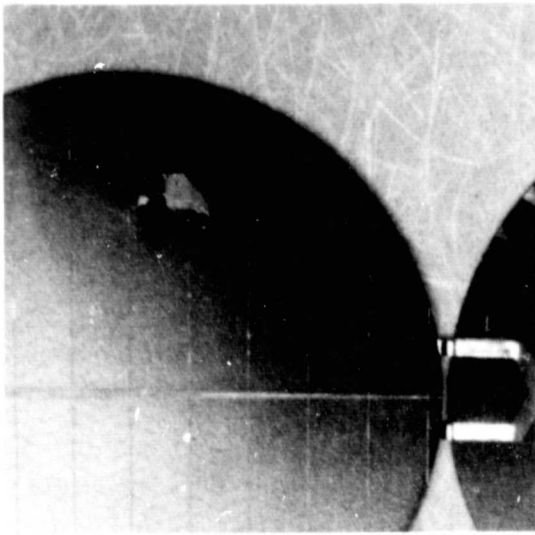
Figure 4-7. Results of Dirt Tests

both a lower initial decrease than that of the silicone rubber and a tapering off of the accumulated effect. The difference between the levels of short-circuit current loss of glass and silicone rubber modules presented in the figure is substantial, and conflicts with data obtained during the previous year, which showed both types of modules losing about six percent per month. No explanation for the paradox is evident. A review of the data showed nothing unusual about either set. Another perplexing result was related to embedded dirt. The arrows adjacent to the silicone rubber data correspond to the average differences between the clean module data and the initial data of May 12. Prior to this date the silicone rubber modules went through a heavy-duty cleaning to remove as much of the embedded dirt as possible. According to the data, in the five week period after May 12 the modules acquired a new four percent embedded dirt layer which essentially did not change throughout the rest of the five month test. Perhaps in the process of cleaning the modules the surface was made receptive to acquiring this new layer.

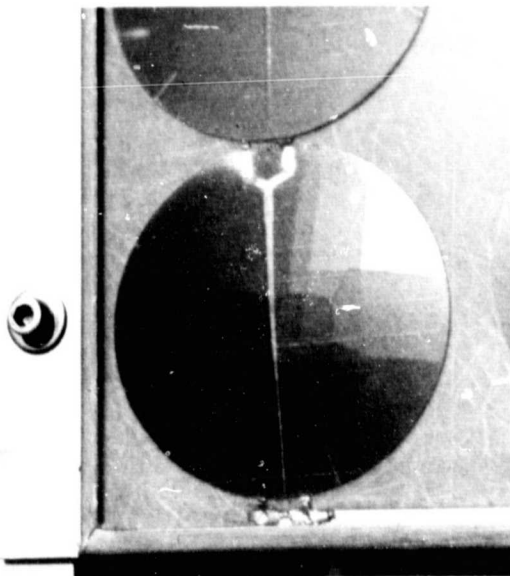
D. PHYSICAL STATUS OF MODULES

Collectively the modules all over the continent are enduring quite well. Those near the ocean, particularly where humidity is high such as at Key West, appear to have suffered the most; those in cold, high UV, and rainy environments seem to be least affected. The Block II and Block III modules are enduring better than Block I modules, and the glass superstrate modules are enduring best of all.

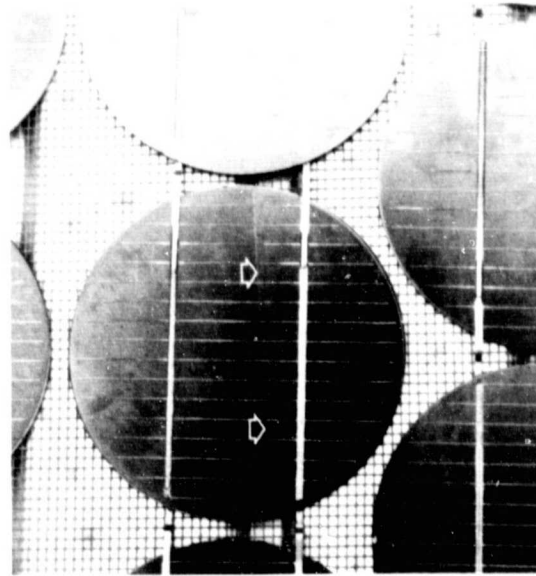
Over the past three years, because of the sheer number of modules deployed, virtually everything that can happen to them has happened: encapsulants have delaminated, cells have cracked, modules have been subjected to hail and 130 MPH winds, birds have eaten the encapsulants, and modules have been attacked and maliciously damaged by vandals. Figures 4-8 through 4-11 contain some typical examples of occurrences in the field.



Impact cracks at the JPL site, probably caused by hail



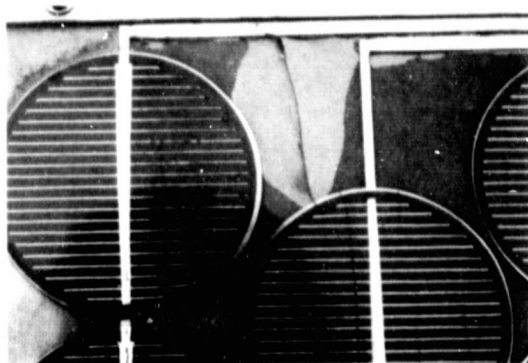
Cracked and bowed cell



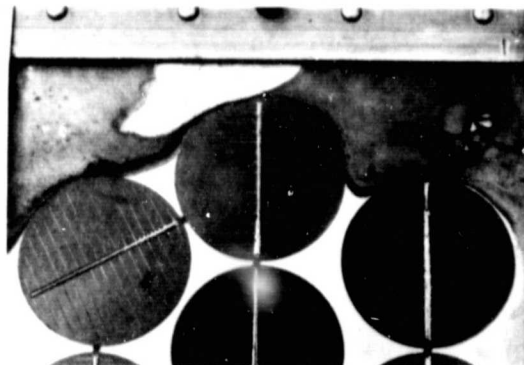
Typical rim-to-rim crack

Figure 4-8. Cracked Cells

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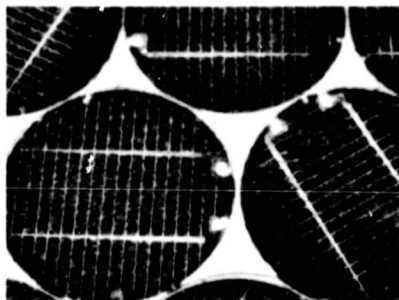


Encapsulant delamination

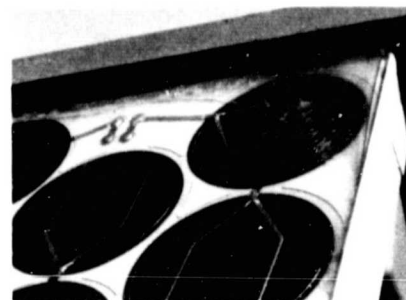


Dirt between substrate and encapsulant

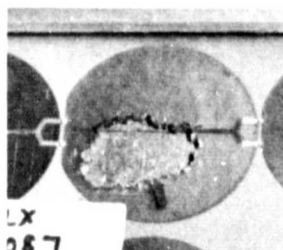
Block I module delamination. Much less delamination was observed with Block II and Block III modules.



Bubbles in encapsulant.
Cover material is glass.

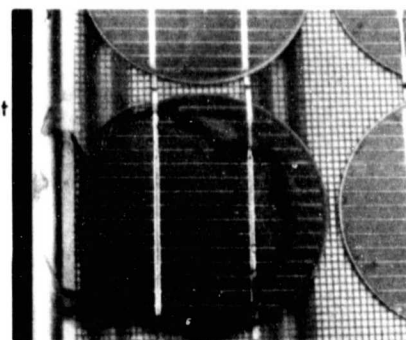


Encapsulant peeling away from cell and substrate (Houghton). Less severe examples of this type of delamination were observed elsewhere.



Encapsulant damaged from bird pecking (Goldstone)

Large pieces of encapsulant were missing on several silicone rubber modules.



Cracked glass superstrate. Although the glass has been cracked for some time, the integrity of the module remains intact.

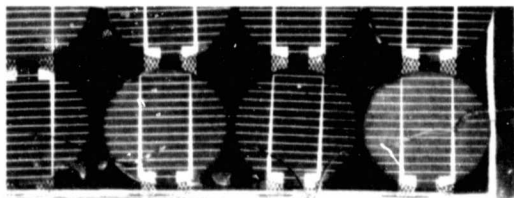


Figure 4-9. Encapsulant Problems

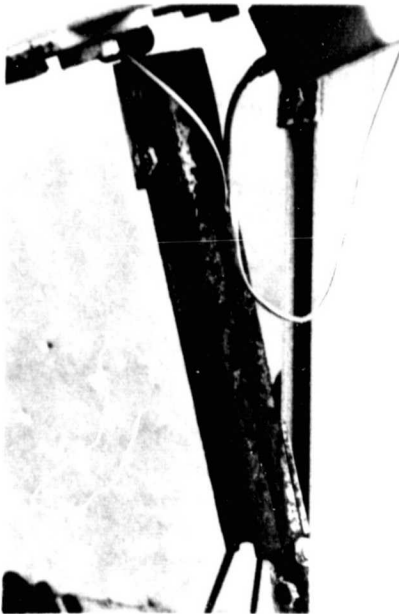


Deterioration of electrical connector

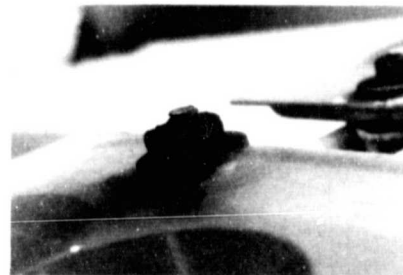


Deterioration of wiring protective boot

In general, wiring and connectors were in good condition. They were more susceptible to deterioration in dry, cold, or corrosive environments such as Dugway.

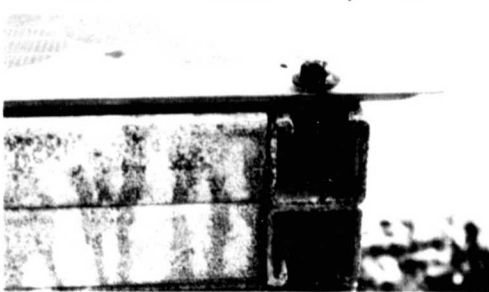


Stands at the continental sites are made from galvanized Unistrut material. Module frames did not show similar signs of corrosion, however some of the peripheral bolts and nuts did.



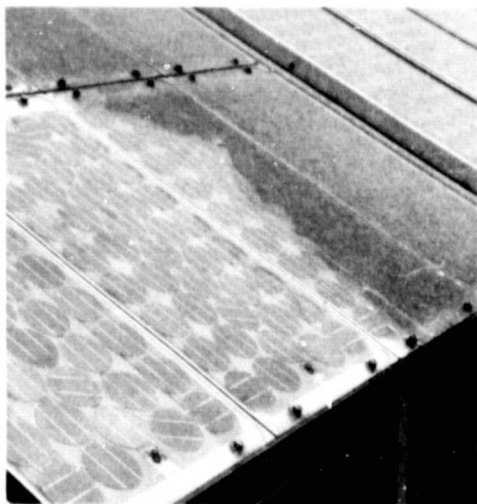
Hardware corrosion at Key West

▲ Corrosion on stands at Key West after 22 months in field

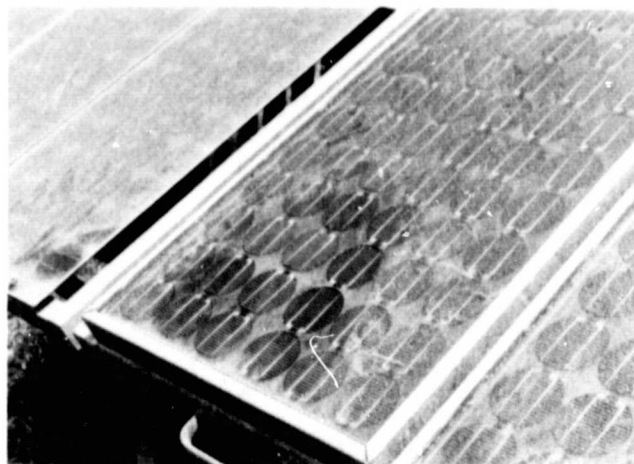


Corrosion on stand at Pt. Vicente after 14 months in field. Stands are constructed of galvanized steel.

Figure 4-10. Stands and Wiring

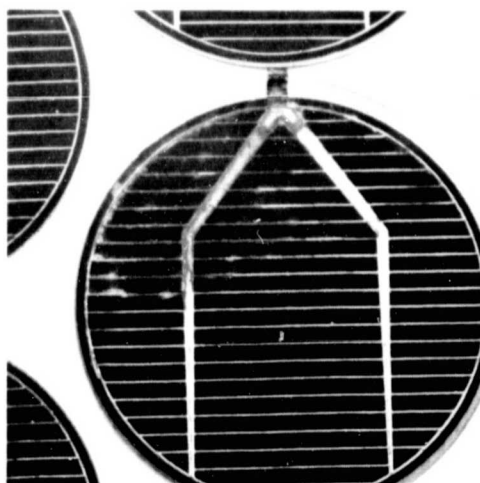


Silicone rubber modules

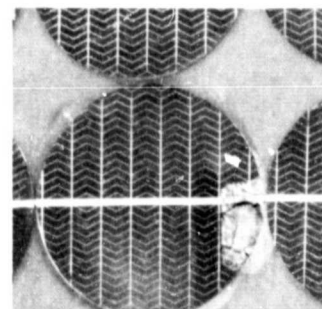


Glass modules

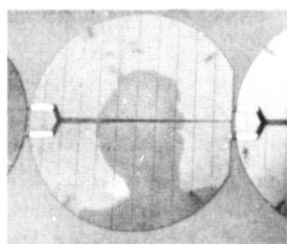
Eleven months of accumulated dirt at Pt. Vicente. Portions of the modules have been wiped clean.



Conductor corrosion. A considerable amount of this was observed, possibly the result of inadequate flux removal during fabrication.



Burned cell and encapsulant. Cell undoubtedly was operating in reverse bias.



Block I module cell discoloration



Module damage by vandalism at New Orleans (module still functioning).

Figure 4-11. Dirt and Other Miscellaneous Problems

SECTION V

FUTURE PLANS

The field testing activity has been in existence for a little more than three years. It is worthwhile at this juncture to review the testing philosophy and decide whether some revisions are in order. When the field testing program was established, the principal goal was to obtain quantified degradation data. As initially conceived the program would provide a series of curves, one for each type of module and environment, showing power degradation as a function of time. So far, however, the modules have not degraded slowly. All our experience to date indicates that electrically, modules change abruptly as the result of some traumatic experience such as a cracked cell. It is reasonable to assume that over a very long period of time some slow degradation patterns will develop because of material deterioration, but within our experience this has not occurred.

Other developments affecting our test strategy are:

- (1) The design of state-of-the-art modules has shifted from use of silicone rubber to glass for encapsulation.
- (2) Our testing capability has grown from a state of infancy to one of maturity.
- (3) Special portable equipment has and is being fabricated which will permit the acquisition of high quality in-situ data, almost on a par with what can be obtained at the JPL site.
- (4) The number of sites has been expanded from three maintained locally to a continental network of sixteen covering virtually all environments.
- (5) Results from application tests have shown that failure and degradation of modules is often related to system design and operation.
- (6) A large procurement (Block IV) of state-of-the-art modules is scheduled for Spring 1980.

Because of all of the above factors and the excellent opportunity presented by the Block IV procurement, major changes in field testing operations are planned for next year.

- (1) The test strategy will be reoriented toward the investigation and isolation of degradation mechanisms and away from attempts to quantify degradation rates and gather failure statistics.

- (2) Block IV modules will be deployed at all 16 sites and become the primary source of data. Some reorganization of the sites and removal of existing modules will be required.
- (3) The effects of array circuits and array/module loading on module degradation will be investigated at JPL by means of our unique capability to continuously monitor individual module behavior as well as that of total arrays.

To accommodate the Block IV deployment and eliminate modules no longer useful, the following revision of module inventory is planned:

- (1) JPL Site. All Block I modules with the exception of the Spectrolab modules will be removed. The Block II inventory will be cut in half. The remaining half will consist of both degraded and non-degraded modules. The controlled dirt tests will be discontinued. Modules dedicated to dirt testing will be removed. A 6 to 12-module array will be set up for array/module loading tests.
- (2) Southern California Remote Sites. All Block I and III modules, with the exception of the Spectrolab modules, will be removed. The Block III modules were chosen for removal because they are similar to Block II modules but have less time in the field. It is anticipated that in about two years the Block II modules will also be removed.
- (3) Continental Remote Sites. All modules, with the exception of the Spectrolab modules, will be removed.

In general the basic test schedule will remain the same: daily data will be obtained at the JPL Site, triennial data at the Southern California Remote Sites, and annual data at the Continental Sites. In addition, approximately once a month, three to five sets of data will be obtained on each module at JPL at different times of the day in order to investigate the effects of temperature. Perhaps the greatest procedural change planned is to use the data system to perform ongoing analyses. With the addition of the tape drive unit and the eventual entering of remote site data into the computer, the potential is unlimited.